Bull. Astr. Soc. India (2003) 31, 215–221

Did Radio Galaxies Play a Major Role in the Evolution of the Universe?

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Abstract. During the 'quasar era', at $z \sim 2-3$, radio galaxies had a much higher comoving density; however, such sources are only detectable for small fractions of their active lifetimes, thanks to expansion losses and inverse Compton losses against the much more intense cosmic microwave background. Combining models for the evolution of the size and luminosity of double radio sources with cosmological simulations of the cosmic web of baryonic material, we find that during the quasar era a large volume fraction of this web was pervaded by the lobes associated with generations of double radio sources. These overpressured, expanding radio lobes could compress gas clouds in the space engulfed by them and trigger global starburst activity. In the process, radio galaxies could have also seeded the IGM with an average magnetic field $\sim 10^{-8}$G; moreover, they could have played an important role in the widespread metal pollution of the IGM.

Keywords : galaxies: radio – intergalactic medium: general – stars: formation

1. Introduction

Between redshifts of 2–3 and the present epoch the comoving space density of powerful radio galaxies (RGs) has declined by a factor of nearly 1000 (e.g. Willott et al. 2001). Perhaps uncoincidentally, the star formation rate also has declined substantially since $z > 1.5$ (e.g. Archibald et al. 2001; Chary & Elbaz 2001). Most old and large RGs are very difficult to detect in surveys and only the youngest can be seen at high redshifts because of severe adiabatic and inverse Compton losses (e.g. Blundell, Rawlings & Willott 1999, hereafter BRW). Cosmological simulations indicate that most of the matter that will form galaxies by the current epoch was in the

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form of filaments that filled only a small portion of the universe at those redshifts (e.g. Cen & Ostriker 1999). Combining these recent findings, we concluded that the formation of many of those galaxies may have been triggered or accelerated by overpressured radio lobes, which probably filled a substantial portion of the cosmic filaments then (Gopal-Krishna & Wiita 2001 – hereafter GKW01; Gopal-Krishna, Wiita & Osterman 2003; Osterman, Wiita, Barai & Gopal-Krishna, in preparation). Such huge radio lobes probably seeded much of the intergalactic medium (IGM) with magnetic fields (GKW01; see also Kronberg et al. 2001 and Furlanetto & Loeb 2001 for independent arguments supporting this conclusion). Furthermore, RGs can contribute significantly to the spreading of metals widely through the IGM and into protogalaxies (Gopal-Krishna & Wiita 2003, hereafter GKW03).

2. Reduced Radio Visibility and Radio Luminosity Functions

All recent models of RG evolution (Kaiser, Dennett-Thorpe & Alexander 1997; BRW; Manolakou & Kirk 2002) find that radio flux declines dramatically both with increasing source size, D (adiabatic losses) and with z (inverse Compton losses off the more intense cosmic background radiation). Observed distributions of radio luminosities, sizes, redshifts and spectral indices can best be fit by models that require RG engines to have active lifetimes, $T \simeq 5\times10^8$y and to have a distribution of beam powers $\propto Q_0^{-2.6}$ (BRW; Osterman et al., in prep.). The gas density through which the jets propagate falls with distance as $n(r) \sim n_0(r/a_0)^{-\beta}$, with $n_0 = 1.0\times10^{-2}\mathrm{cm}^{-3}$, $a_0 = 10$ kpc, and $\beta = 1.5$ (BRW), so the total linear size of the RG is given by $D(t) = 3.6a_0\left(t^3 Q_0/a_0^5 m_p n_0\right)^{1/(5-\beta)}$

For most RGs, particularly those at $z > 2$, it was found that the central engines remain active for much longer times than those galaxies are detected in flux limited surveys; thus they should grow to very large linear sizes ($D(T) > 1$ Mpc) (BRW; GKW01). We find that the visibility time, $\tau \propto Q_0^{1/2}$, so a correct estimate of the actual number of RGs requires multiplying those detectable in flux-limited surveys by a correction factor (T/τ) of roughly 50 for powerful RGs during the quasar era (GKW01).

Because the additional cosmological dimming goes as $(1+z)^{-4}$, the already faded extended lobes of many high-z giant RGs that are still active will not be seen (e.g. Neeser et al. 1995; Gopal-Krishna, Wiita & Saripalli 1989). The high probability of 'missing' faded radio lobes resulting from *past* activity is emphasized by the extraordinary effort required to detect even the giant outer lobes of the nearby radio galaxy M87 (Owen, Eilek & Kassim 2000). 'Compact double' radio sources, several of which are found to have faint, diffuse radio structures (e.g. Schoenmakers et al. 1999), provide further examples of this difficulty. Associating these faint structures with their true core, or even with each other, would have been impossible had these sources been imaged only a few hundred years ago, when their present central radio components were not yet been born. Other recent evidence for the long duration of AGN activity ($> 10^8$yr) come from Chandra X-ray (Barger et al. 2001) and the Sloan Digital Sky Survey optical studies (Miller et al. 2003). Although typical RG lifetimes are often quoted as only $\sim 3\times10^7$yr (e.g. Kaiser 2000) these are based on questionable (e.g. Blundell & Rawlings 2000) spectral ageing arguments, and perforce cannot include analysis of old, faded RGs which fall below flux or surface brightness thresholds.

Radio Luminosity Function (RLF) studies are problematic when there is incomplete knowledge of the redshifts of the RGs; however, results based upon the 3CRR, 6CE and 7CRS surveys with different flux limits have the advantage of having 96% of their redshifts known (Willott et al. 2001). Powerful (FR II type) RGs are nearly 3 dex above the local RLF by $z \sim 2$, and their RLF varies little out to the beginning of the quasar era at $z \sim 3$, while it appears to decline at higher z (Willott et al. 2001). Furthermore, the RLF at that z is nearly flat for over a decade in radio power above $P_{151} \geq 10^{25.5}$ W Hz^{-1} sr^{-1}, which is where the FR II sources are most numerous.

Coupling these results with the correction factor discussed above, we first find the actual *proper* density of powerful radio sources lasting for an interval T at $z \simeq 2.5$. Next we integrate over the peak of the RLF and note that several generations of RGs will be born and die within the ~ 2 Gyr duration of the quasar era. This leads us to the total proper density, Φ, of intrinsically powerful radio sources: $\Phi = 7.7 \times 10^{-3}$ Mpc^{-3}, which is independent of the assumed value of T, and nearly independent of cosmological model parameters (for details, see GKW01).

3. Radio Lobes, the Relevant Universe, and Star Formation

Numerical evolutions of ΛCDM universes indicate that at $z \sim 0$, roughly 70% of baryons are in a cosmic web of filaments of warm-hot gas and embedded galaxies and clusters that together occupy only about 10% of the volume of the universe (e.g. Cen & Ostriker 1999). But at $z \sim 2.5$ the growing network of filaments comprised a still smaller fraction of the total volume, $\eta \simeq 0.03$. The radio lobes ejected from early RGs would mostly remain within the filaments (GKW03). Thus it is in this relatively small, 'relevant universe', where new galaxies are formed out of denser gas clumps, and so we only are concerned with what fraction of this relevant universe the radio lobes permeated. We find that the mean volume of a radio source is $\langle V(T)\rangle \simeq 2.1(T/5 \times 10^8\mathrm{yr})^{18/7}$ Mpc^3, and thus, the volume fraction of the relevant universe which the radio lobes born during the quasar era cumulatively swept through is roughly given by (GKW01)

$$\zeta = \Phi\ \langle V(5 \times 10^8\mathrm{yr})\rangle\ (0.03/\eta)(5/R_T)^2 \simeq 0.5, \qquad (1)$$

where $R_T \sim 5$ is the typical length-to-width ratio of an RG. The energy density injected by the lobes into the cosmic web of filaments is $u \simeq 2\times10^{-16}$ J m^{-3} for those same canonical parameters. Because $\langle V(T)\rangle$ is a sensitive function of T, if the typical RG lifetime is $< 10^8$ yr, then $\zeta < 0.01$ and $u < 9 \times 10^{-18}$ J m^{-3} (GKW01).

The alignment effect between extended optical emission lines and radio lobe directions (e.g. McCarthy et al. 1987; Chambers et al. 1987) can be partially explained by star formation that could be triggered by these expanding overpressured lobes (e.g. Begelman & Cioffi 1989; Rees 1989). Recent hydrodynamical simulations including cooling (Mellema, Kurk & Röttgering 2002) confirm that star formation is likely to occur through cloud fragmentation, cooling and compression. These compressed regions may correspond to the frequently observed clumpy structure of newly forming galaxies (e.g. Pentericci et al. 2001). We showed (GKW01) that FR II sources produce overpressures at $D = 50$ kpc amounting to factors of 10^2–10^4, corresponding to Mach numbers of 10–100 for the bow shock. Overpressures of factors > 10 (and Mach numbers above 3) are maintained out to $D > 1$ Mpc. These conditions are capable of producing extensive starbursts.

4. Widespread Magnetization and Metallization of the IGM

Another important implication of this scenario is that RGs can inject a substantial amount of magnetic energy into the IGM at $z \sim 2-3$. If magnetic fields are preferentially distributed in the cosmic filaments where the relevant IGM is also concentrated, then fields of up to $\sim 10^{-6}$G within those filaments are allowed by Faraday rotation measurements of quasars (Ryu et al. 1998). A substantial fraction of the IGM also may have been permeated by magnetized outflows from stars in galaxies (Kronberg, Lesch & Hopp 1999).

While the idea that jets in radio galaxies could magnetize the IGM is not new, those earlier investigations concluded that either only minute magnetization levels or insignificant volume coverage would be attained (e.g. Daly & Loeb 1990; Rees 1994). In GKW01 we showed that during the quasar era, the permeation of the IGM by the expanded lobes of radio galaxies could have seeded the IGM with an average magnetic fields of $\approx 10^{-8}$G, which matches the IGM field strengths inferred by Ryu, Kang & Biermann (1998) and by Furlanetto & Loeb (2001). The latter authors, considering isotropized magnetized bubbles fed by quasars, have argued that the quasar population is capable of polluting $\sim 10\%$ of the entire space with magnetic fields. From another set of independent arguments, Kronberg et al. (2001) have concluded that the accretion energy released by radio-loud QSOs at $z \sim 2-3$ is adequate to magnetize the IGM to the level of its thermal energy, *provided* the radio lobes can expand to fill up the IGM.

The question of the transport of metals from their production sites in the ISM of galaxies, to the Mpc-scale IGM or even voids with a mean density $< 10^{-4}\text{cm}^{-3}$ or less has garnered much recent attention (e.g. Schaye et al. 2000, 2003; Theuns et al. 2002). Lyman-break galaxies at $z > 3$ often have metalicities around 0.1 solar and damped Lyman-α clouds have metalicities $\sim 10^{-2.5}$ solar (e.g. Steidel et al. 1999; Pettini et al. 2001). Supernova explosions in star-forming galaxies are found to fail by at least an order-of-magnitude to pollute the whole IGM to the metallicity levels observed within the available time, although the ease of loss of metals from the numerous dwarf galaxies might suffice (e.g. Gnedin & Ostriker 1997; Ferrara et al. 2000; Shchekinov 2003).

We recently proposed (GKW03) a new mechanism for large-scale metal transport: the sweeping of the ISM of star-forming galaxies by the expanding giant radio lobes during the quasar era, or even earlier. Also, outflowing radio jets will drag a significant fraction of the gas in their host galaxy out with them, most of it compressed into a shell along the bow shock outside the lobes, as illustrated by numerical simulations of jets leaving a galaxy's ISM (e.g. Hooda & Wiita 1998). Such enriched gas can then be spread over distances exceeding 1 Mpc over the course of $\sim 10^8$ years. Once this expanding gaseous shell interacts with denser clouds in the ICM or IGM, not only will extensive star formation be triggered, but this star-forming region will include some of this swept up enriched gas. Since much of it should have remained in the bow-shock region, the dilution is much less than if the enriched gas were spread throughout the entire radio lobes. An advantage of this mechanism is that heating of the denser gas is less of a problem than when the metals are conveyed by supernova driven winds. But even with the much greater density of RGs during the quasar era, it is not clear if they are numerous enough to produce the apparently rather uniform metal distributions at $z > 3$; however, we note that the claims (Schaye et al. 2000, 2003) of metallization in the voids as well as the cosmic web have recently been called into question by two independent analyses (Aracil et al. 2003; Pieri & Haehnelt 2003), so this may not be a real problem for our scenario.

Not only can radio lobes contribute to "metallization" by dragging along some of the enriched gas from their host galaxy, but they will otherwise affect young galaxies which they envelop. If these young galaxies have a multi-phase medium and are not too dissimilar from local galaxies in this regard, then ram pressure stripping of their ISM (Gunn & Gott 1972) produced by these expanding radio lobes can be important (GKW03). We find this ram-pressure is adequate to remove most of the diffuse ISM from a typical spiral, and would be even more effective in stripping the diffuse gas from smaller, recently forming, galaxies at $z > 2$. Note that individual AGN may go through several generations of nuclear activity producing radio jets and lobes. The first episode could trigger starbursts, or even new clumpy galaxy formation, in nearby overdense regions. Subsequent radio lobes hitting that newly formed galaxy a few hundred Myr later could sweep out most of the enriched gas it had already produced, thereby metallizing more distant regions. These metals could contribute to the seeding of additional clouds which are, in turn, triggered to collapse into stars during these subsequent active periods.

5. Conclusions

Despite the sparse population of powerful radio sources in the local universe three large factors synergise to make RGs important for galaxy formation during the quasar era.

- Their comoving density was roughly 1000 times higher at $\sim 2 < z <\sim 3$. Moreover, this quasar era was long enough to encompass a few generations of RGs.
- Because of severe inverse Compton and adiabatic losses only a few percent of these RGs are detected in the surveys used to produce the RLFs (i.e., those with essentially complete redshift data). Detection of such faded radio lobes expected in a large fraction of RGs at high redshifts is a strong challenge to future generations of radio telescopes.
- The fraction of the volume of the universe occupied by the material during the quasar epoch that would finally condense into clusters of galaxies was only a few percent, so these lobes only had to permeate this 'relevant universe' rather than the entire universe.

As all current models of RG evolution indicate that the lobes are overpressured and supersonically expanding into the relevant universe, it is very plausible that many massive starbursts, and even many galaxies, formed in this fashion at $z \sim 2 - 3$. Other key results are: 1) RGs were likely to have been capable of widespread seeding the IGM with magnetic fields of the appropriate strength; two other independently motivated and distinct analyses lead to similar conclusions (Furlanetto & Loeb 2001; Kronberg et al. 2001); 2) The sweeping up of the ISM of the galaxies and star-forming clouds by the expanding lobes of RGs suggests a natural way to spread metals produced in the first stellar generations over large volumes. We are working out details of these and other (e.g., Sunyaev–Zeldovich effect) implications of this scenario. We are also considering wider ranges of the parameters describing both radio sources and the confining medium, so as to test the robustness of our conclusions.

Acknowledgements

GK thanks the SOC and the LOC for the excellent organization of the meeting. He acknowledges helpful discussions with A. Lecavelier and P. Petitjean concerning the metallization of the IGM. PJW is grateful for support from RPE funds at GSU and for continuing hospitality at the Department of Astrophysical Sciences at Princeton.

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